# The High Energy-Density instrument at the European XFEL


U. Zastrau[1], K. Appel[1], C. Baehtz[2], N. Biedermann[1], T. Feldmann[1], S. Göde[1], Z. Konôpková[1], M. Makita[1], E. Martens[1], W. Morgenroth[4], M. Nakatsutsumi[1], A. Pelka[2], T. Preston[1], A. Schmidt[1], M. Schölmerich[1], C. Strohm[4], K. Sukharnikov[1], I. Thorpe[1], T. Toncian[2], and the HIBEF user consortium[4]

[1]European XFEL, Germany [2]HZDR, Germany [3]Univ. Frankfurt, Germany [4]http:\\www.hibef.de


## Science case

The science scope of the HED instrument focuses on states of matter at high density, temperature, pressure, electric and/or magnetic field. Major applications are high-pressure planetary physics, warm- and hot- dense matter, laser-induced relativistic plasmas and complex solids in pulsed magnetic fields. These extreme states can be reached by different types of optical lasers, the X-ray FEL beam and pulsed coils. User operation at the HED instrument is foreseen to start in Q2 2019.

## Properties of XFEL undulator for HED (SASE2)

**SASE2 undulator**

- Hard X-ray source: 3 – 25 keV photon energy, $10^{-3}$ SASE bandwidth, $10^{-5}$ self-seeded
- Repetition rate: 10 Hz bunch trains with up to 2700 pulses
- Pulse energy: $10^{8}$ – $10^{13}$ X-ray photons per pulse / 100 nJ – few mJ
- Pulse duration: 2 to 100 fs (correlates with bunch charge)

**HED instrument X-ray optics & beam characteristics**

- Three mirrors (two for beam offset & one for distribution between HED / MID instruments)
- Monochromators: 4-bounce $Si_{111}$ (5 – 25 keV, ~$10^{-4}$), high-resolution monochromator (~$10^{-6}$)
- Focusing: Be lenses at three positions (229, 857 and 962 m downstream of the undulator exit) resulting in spot sizes of ~200 µm, ~20 µm, and 1 – 3 µm FWHM for 5 – 25 keV
- Split & Delay Line (BMBF project, U Münster): Delays: ~2 ps (20 keV) to ~23 ps (5 keV)

**Repetition rate**

- 4.5 MHz, 1 – 10 Hz, shot-on-demand

## X-ray diagnostics available at HED

**X-ray diffraction**

- IC1: gain-switching in-vacuum tiled detectors (ePIX 100, Jungfrau), motorized
- IC1 and IC2: large area detectors in air (or in air pocket in vacuum): Perkin-Elmer
- GaAs AGIPD on detector bench with central hole (220-ns framing to record bunch pattern)

**Inelastic X-ray scattering**

- Two HAPG von-Hamos spectrometers (ΔE < 9 eV) on motorized rails on vertical breadboard
- Spherical diced Si (533) analyzers for E/ΔE ~$10^{-6}$ high resolution inelastic x-ray scattering

**X-ray absorption spectroscopy**

- Bent Si crystal spectrometers before IC1. Future plan to built a second one after interaction point.

**SAXS, PCI, …**

- Placed on detector bench

**Emission spectroscopy**

- Flexible flat and bent perfect crystals coupled to ePIX100 detectors

## Optical "drivers": intense lasers

**Pump-probe (PP) laser (XFEL.EU)**

- 0.05 - 2 mJ, 4.5 - 0.1 MHz, 15 fs , λ = 800 nm
- 1 - 40 mJ, 4.5 - 0.1 MHz, 900 fs, λ = 1030 nm

**100 – 200 TW short-pulse laser (HIBEF UC)**

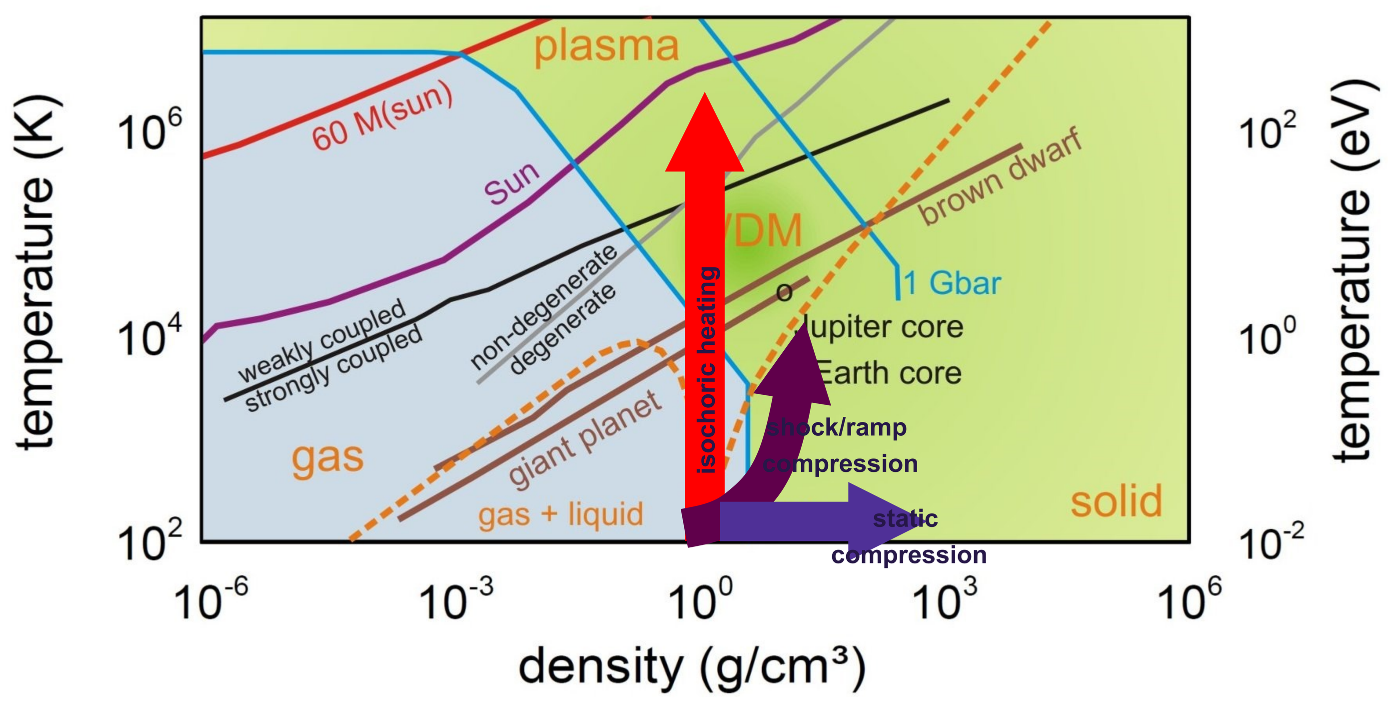
- 4-10 J, >25 fs, 10 Hz, 740 - 860 nm, Ø145 mm

**DiPOLE100-X, 100 J long-pulse laser (HIBEF UC)**

- 100 J, 2 - 15 ns, 10 Hz, 1030 nm
- 75 mm × 75 mm square beam profile

**Optical diagnostics (XFEL.EU & HIBEF)**

- VISAR, SOP & FDI




## Other "drivers"

**Tightly focused X-ray pulses (XFEL.EU)**

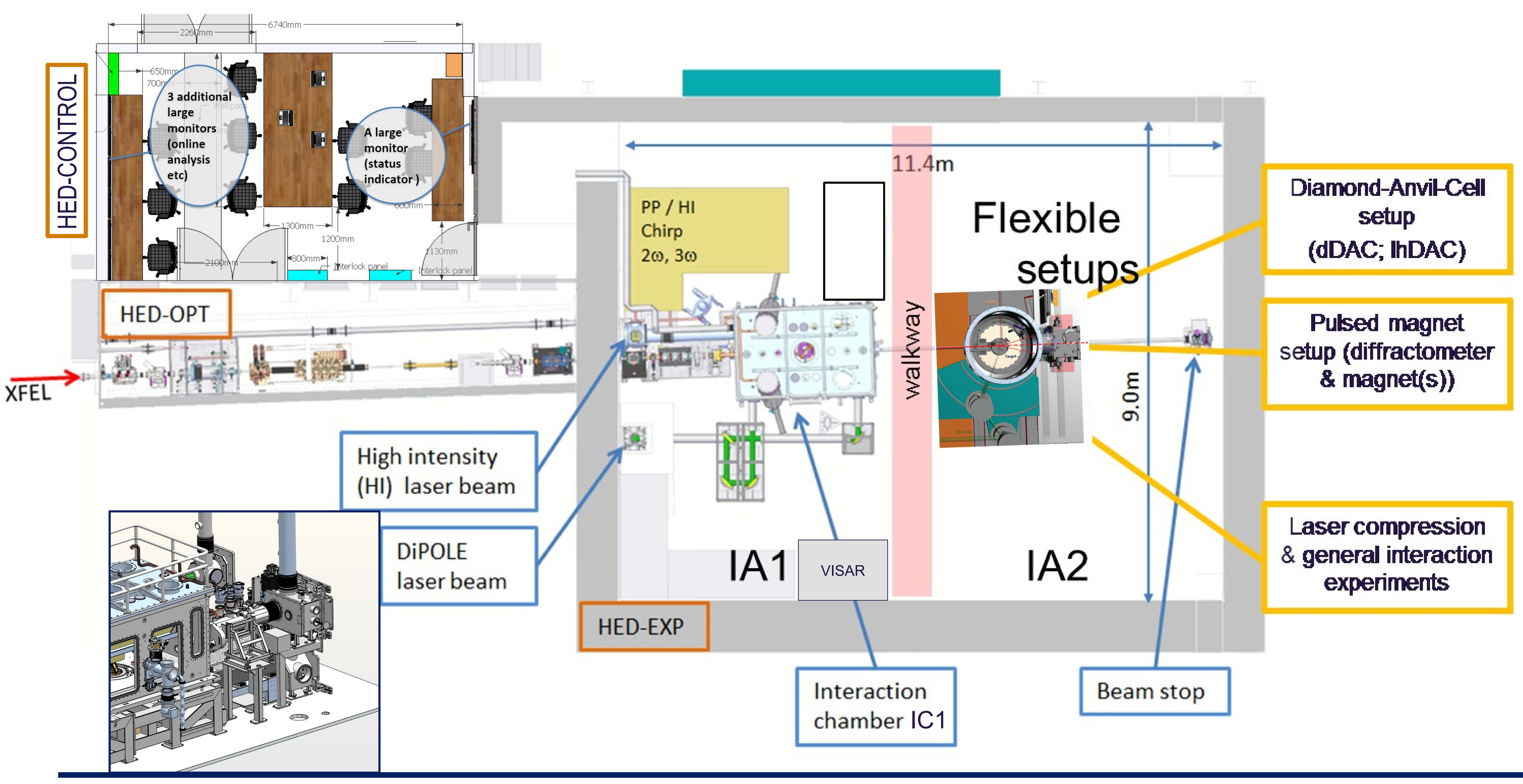
- 5 - 25 keV, up to few mJ, 0.1 - 4.5 MHz, <100 fs
- X-ray Split & Delay Line with delays up to 25 ps

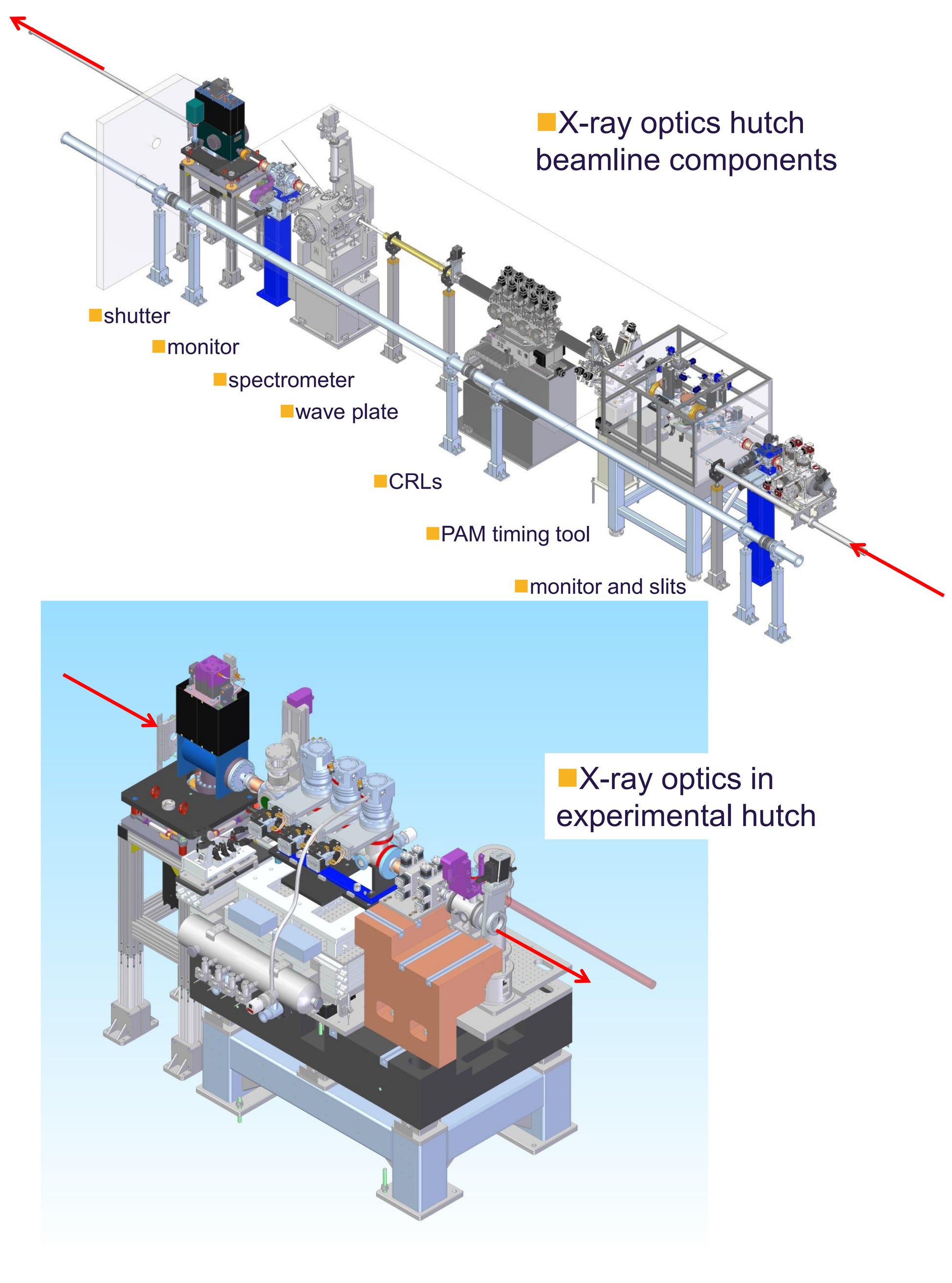
**60 T pulsed magnetic fields (HIBEF UC)**

- 100 MJ pulser
- Rise time ~0.6 ms matching to X-ray pulse train
- Several coil layouts and goniometer

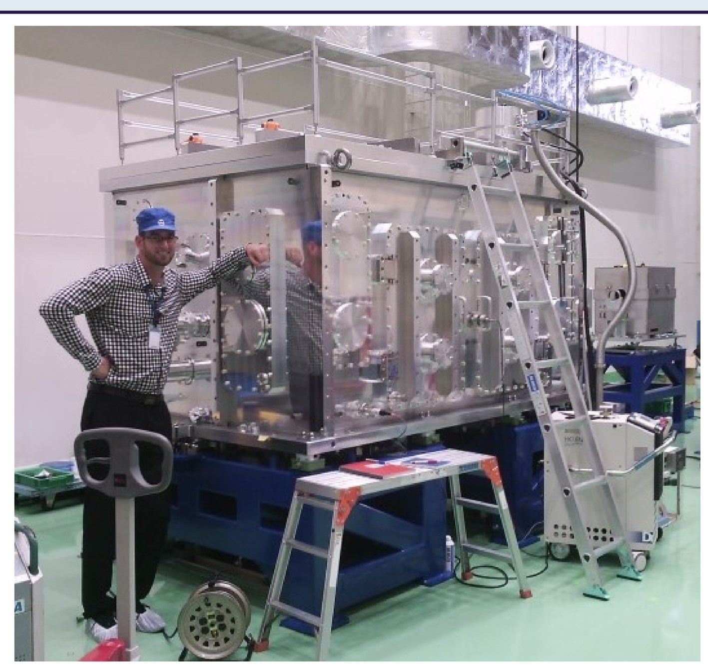
**Diamond Anvil Cells DAC (HIBEF UC)**

- Dynamic, membrane, and double-stage DAC
- Pulsed laser heating
- Dedicated second interaction chamber

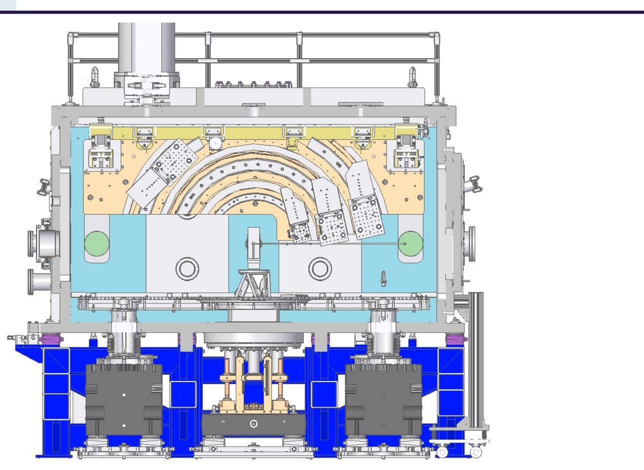


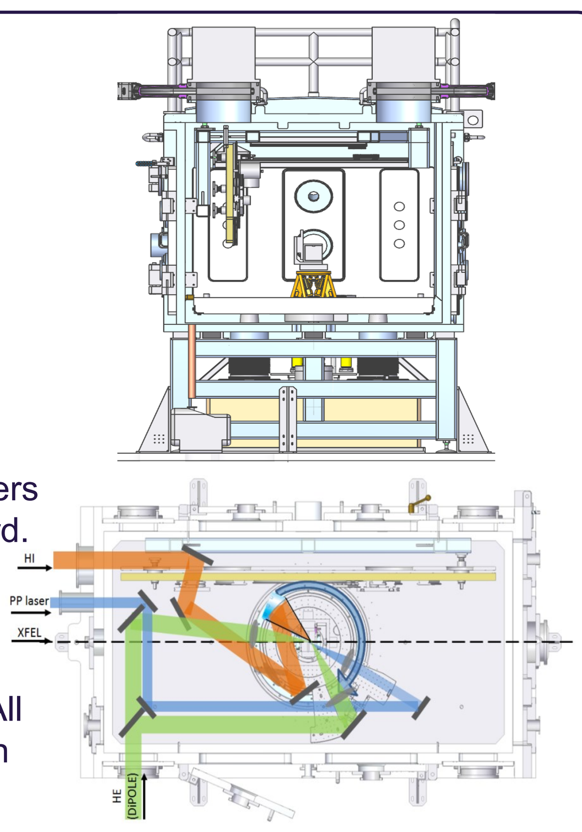

## HED Interaction chamber "IC1"



- All-aluminum chamber to avoid activation during relativistic laser-plasma experiments.
- Built by Toyama, Japan. Installed in May 2017.

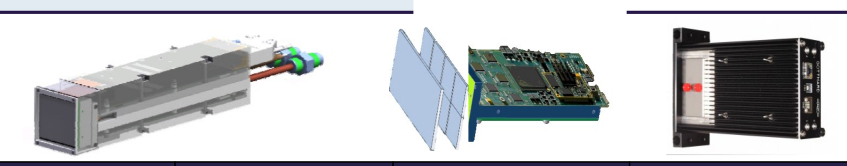


- Circular rails for mounting detectors, spectrometers or analyser crystals fitted to a vertical bread board.



- Some beam paths of the optical lasers inside the chamber IC1. All mirrors are adjustable in position and angle.

## X-ray detectors



| Parameters | ePix100 (SLAC) | ePix10k (SLAC) | Jungfrau (PSI) | Gotthard-I (PSI) |
|---|---|---|---|---|
| **Sensor** | 300 µm Si | 300 µm Si | 320 µm Si | 320 µm Si |
| **Sensor size** (pixel) | 704 × 768 (35×38 mm²) | 352 × 384 (35×38 mm²) | 512 × 1024 (40×80 mm²) | 1 × 1280 (8×64 mm²) |
| **Pixel size** (µm) | 50 | 100 | 75 | 50 |
| **Dynamic range** | $10^{2}$ (@ 8 keV) | $10^{4}$ (@ 8 keV) | $10^{4}$ (@ 12 keV) | $10^{4}$ (@ 12 keV) |
| **Noise** (eV) | ~260 | ~560 | ~450 | ~900 |
| **Repetition rate** (Hz) | 120 | 120 | 2,000 0.5 MHz in burst mode, 16 images on-chip memory | 40,000 0.8 MHz in burst mode, 128 images digital buffer |
| **# of modules** | 2 | 3 | 4 | 2 |


ulf.zastrau@xfel.eu


www.xfel.eu/research/instruments/HED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Westfälische Wilhelms-Universität Münster
DESY
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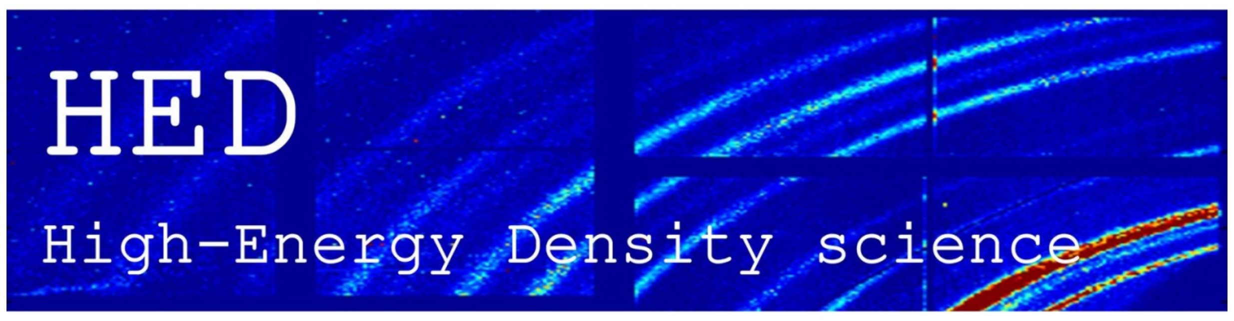



# HED Instrument Parameters for Early User Operation

All parameters are subject to change, depending on the commissioning process of both the accelerator and the instrument.

For more information, please contact:
**ulf.zastrau@xfel.eu**

## X-Ray Photon Beam Parameters

| | | |
|---|---|---|
| photon energy | **9 keV** | Adjustable 7-25 keV |
| pulse energy | **0.5 – 1 mJ** | Up to 2 mJ |
| photons per pulse | **3 x $10^{11}$** | Estimated by SPB/SFX, FXE |
| pulse duration | **10 fs** | Derived by theory group |
| spot size on sample | **min. 1 µm** | Variable up to ~ mm |
| photons/µm$^2$ on sample | **$10^9$ -$10^{10}$** | Derived by SPB/SFX, FXE |
| train repetition rate | **10 Hz** | Fixed |
| Intra-train repetition rate | **1.1, 4.5 MHz** | Possibly 100 kHz; arbitrary |
| No. of bunches per train | **1-60** | Possibly up to 300 |
| ΔE/E | **~ 0.2%** | Estimated by SPB/SFX, FXE |

## Detectors

| **Parameters** | **ePix100** | **ePix10k** | **Jungfrau** | **Gotthard-I** |
|---|---|---|---|---|
| | SLAC | SLAC | PSI | PSI |
| **Sensor** | 300 µm Si | 300 µm Si | 320 µm Si (upgr 450 µm Si) | 320 µm Si |
| **Sensor size** (pixel) | 704x768 (35x38 mm$^2$) | 352x384 (35x38 mm$^2$) | 512x1024 (40x80 mm$^2$) | 1x1280 (8x64 mm$^2$) |
| **Pixel size** (µm) | 50 | 100 | 75 | 50 |
| **Dynamic range** | $10^2$ (@ 8 keV) | $10^4$ (@ 8 keV) | $10^4$ (@ 12 keV) | $10^4$ (@ 12 keV) |
| **Noise** (eV) | <280 | <560 | <450 | <900 |
| **Repetition** (Hz) | 120 | 120 | 2,000 * | 40,000 ** |
| **# of modules** | **2** | **3** | **4** | **2** |

* 0.5 MHz in burst mode, 16 images on-chip memory
** 0.8 MHz in burst mode, 128 images digital memory

## Split and Delay Unit

| **X-ray energy** | **Delay** | **Multilayers** |
|---|---|---|
| 5 keV | ~23 ps | **$Ni/B_4C$** (<12 keV) |
| 15 keV | ~4 ps | **$Mo/B_4C$** (8-20 keV) |
| 20 keV | ~2 ps | |

## Spectrometers (diagnostics and experimental)

### Single Shot Spectrometer (CAEP)

| | | |
|---|---|---|
| Crystals | 4x 10 µm **Si** | |
| Energy | **3-15 keV** with grating | **5-25** crystal only |
| Energy resolution (dE/E) | **< 1 x $10^{-4}$** | |
| Detector | Optical CCD (2D) | Gotthard-I (1D) |
| Detector arm rotation | **30° - 90°** | |

### Experimental (Analyser crystals for IXS and hrIXS)

| | | |
|---|---|---|
| 4 high resolution diced analyzers | **Si 533** | 10 mm diameter, R = 1 m spherical |
| 2 mosaic spectrometers | **HAPG 002** | R= 50 and 75 mm, cylindrical 32 mm x 30 mm size |

## Monochromators

### X-ray bandwidth

| | **ΔE/E** | Energy |
|---|---|---|
| SASE | **$10^{-3}$** | 3-25 keV |
| $Si_{111}$ mono | **$10^{-4}$** | 5-25 keV |
| $Si_{533}$ high-res mono | **$10^{-6}$** | 7.494 keV |

## Target delivery

| **Target system** | **Samples** | **Rep rate** |
|---|---|---|
| High precision positioning system | RMT's, wires, structured targets | Shot on demand |
| Fast Sample Scanner | Foil, crystal, powder | 1 – 10 Hz |
| Cryogenic jets | Solid H2, D2, HD, CH4, Ne, Ar | 10 Hz |

## Optical Laser Systems*

| | **λ (nm)** | Max repetition rate | Pulse diffraction | Max. pulse energy |
|---|---|---|---|---|
| PP | **~ 800** | 0.1 – 4.5 MHz | 15 – 300 fs fourier-limited | ≤ 2 mJ |
| PP | **1030** | 0.1 – 4.5 MHz | ~ 1 ps | ≤ 40 mJ |
| HI (Amplitude) | **~ 800** | 10 Hz | ~25 fs | ≤ 10 J |
| HE (DiPOLE) | **515 (1030 fundamental)** | 1 – 10 Hz | 15 ns or shorter | ~100 J at 1030 nm |

* Please inquire HED staff about availability

European XFEL GmbH, Ulf Zastrau, Holzkoppel 4, 22869 Schenefeld, Germany, Phone +49 40 8998-6969, Fax +49 40 8998-1905, ulf.zastrau@xfel.eu
**www.xfel.eu**

# X-ray beam transport and properties at the High Energy Density science instrument at European XFEL

European XFEL

K. Appel[1], C. Baehtz[2], B. Chen[3], T. Feldmann[1], S. Göde[1], Z. Konopkova[1], M. Makita[1], E. Martens[1], W. Morgenroth[4], M. Nakatsutsumi[1], A. Pelka[2]
S. Roling[5], A. Schmidt[1], K. Sukharnikov[1], I. Thorpe[1], and U. Zastrau[1]

[1] European XFEL, Germany, [2] Helmholtz-Zentrum Dresden-Rossendorf, Germany, [3] Chinese Academy of Engineering Physics, People's Republic of China, [4] Frankfurt University, Germany, [5] Münster University, Germany

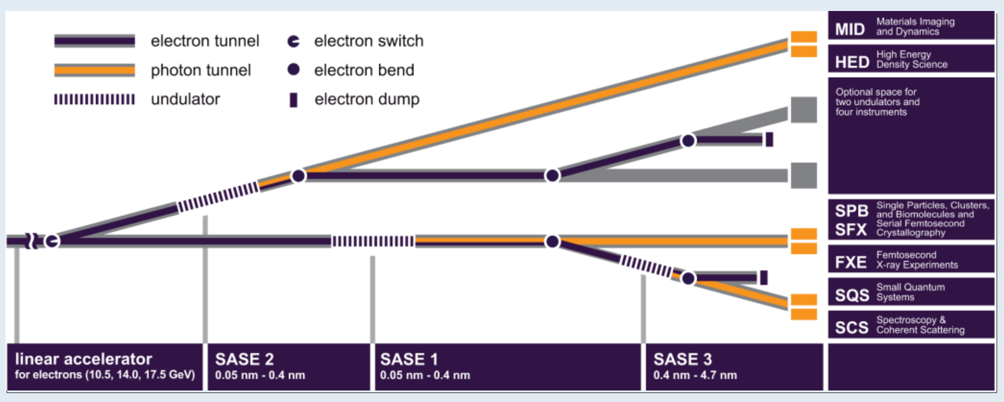

## Abstract

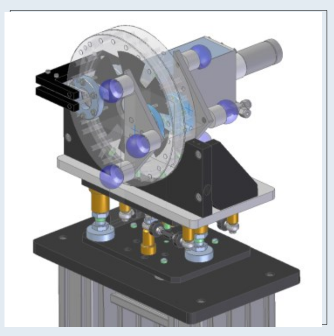
The HED science instrument is located at the **SASE2 undulator**, which produces hard X-rays in an energy range between **3 and 25 keV**. The first 390 m downstream of the undulator source are shared with the scientific instrument MID [1]. A distribution mirror is located at 390 m that allows to stir the beam to the HED science instrument which is located in the experimental hall at about 970 m from the source [2, 3, 4]. As additional **optical elements** we foresee two monochromators, a split and delay unit, a quarter wave plate and four positions for focusing optics in the tunnel and in the experimental hall. This leads to a variety of X-ray beam properties at the sample position, that can be selected for the respective experiment. Major **X-ray beam diagnostics in the HED part of the beamline** comprise on-line monitoring of the arrival time of X-rays and optical lasers [5], an in-situ single-shot X-ray spectrometer combining a diamond grating with a convex Si crystal following the concept of [6], as well as intensity and position monitors.

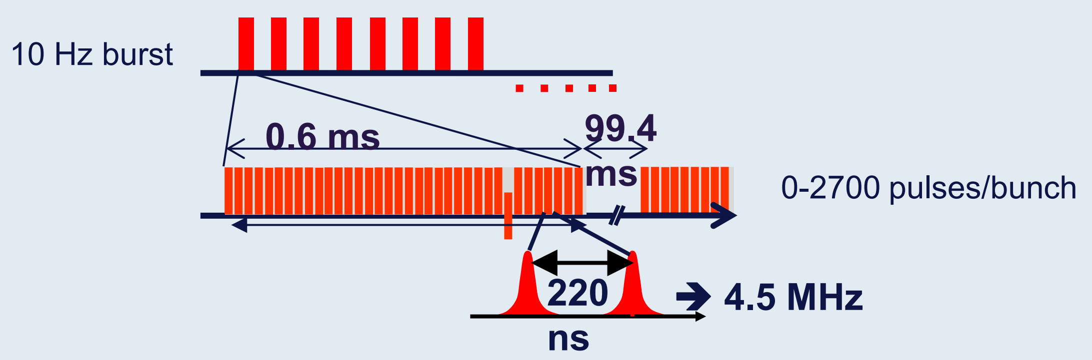

## XFEL beam properties

### SASE2 undulator

| | |
|---|---|
| Hard X-ray source | 3 – 25 keV photon energy, $10^{-3}$ SASE bandwidth, $10^{-5}$ self-seeded |
| Repetition rate | 10 Hz bunch trains with up to 2700 pulses, pulse on demand |
| Pulse energy | $10^8$ – $10^{13}$ X-ray photons per pulse / 100 nJ – few mJ |
| Pulse duration | 2 to 100 fs (correlates with bunch charge) |



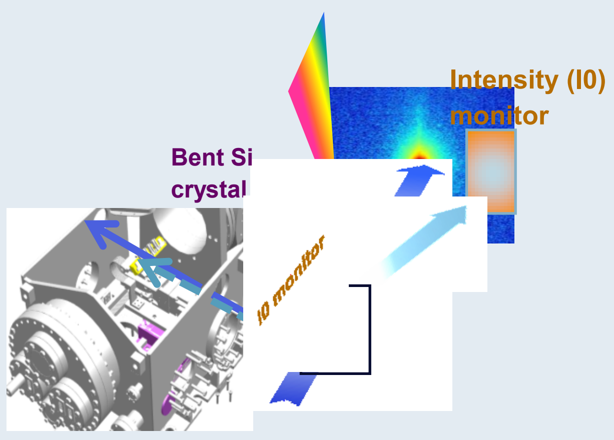



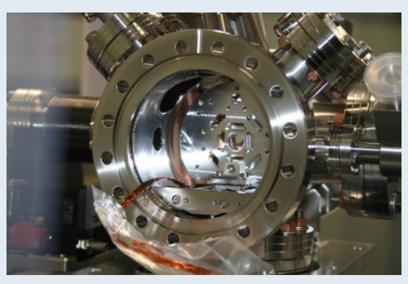



Top, left: Schematic top view of the six first scientific instruments at European XFEL. Top, right: Pulse picker for HED (rotating disk, 10 Hz). Bottom: Schematic of the electron beam time structure.

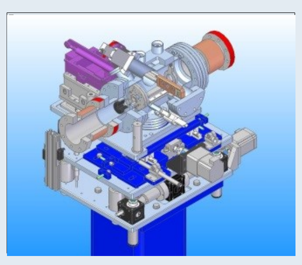
## Key X-ray beam diagnostics

- In-situ single shot spectrometer combining a diamond grating with a convex Si crystal
- In-situ fast intensity monitors based on back-reflection of diamond foils
- Intensity monitors based on fluorescence screens
- Online monitoring of the arrival time between X-rays and optical lasers



Filters:
B-doped CVD diamond
Thickness:
22, 50, 100 and 400 µm

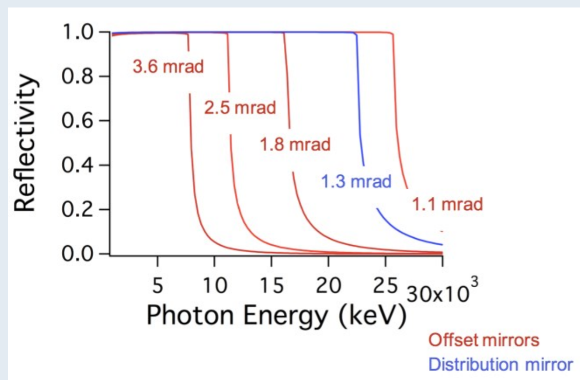


Left: Concept of the single shot spectrometer with technical drawing: the spectrometer crystal can either be used in the direct beam at 10 Hz, or in the full pulse-train using the grating. A intensity monitor for the diffracted beam is available. Right: Technical drawing and picture of the in-situ fast intensity monitor.

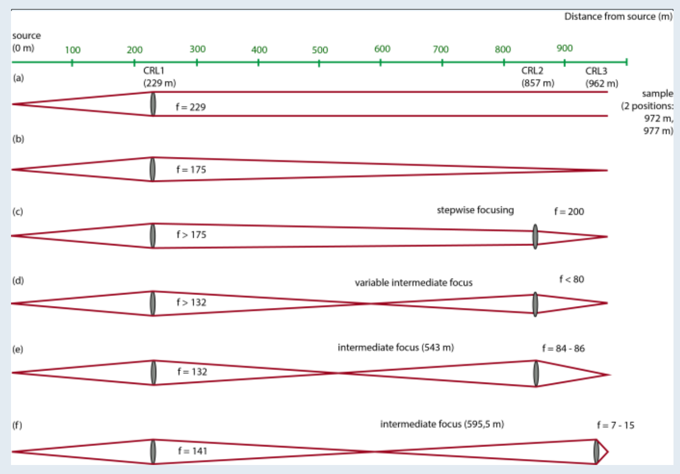
## X-ray beam optics and properties

- Three mirrors (two for beam offset & one for distribution between HED / MID instruments) [1]. Higher harmonics suppression with the mirrors is expected to be in the range of $10^{-6}$.
- Focusing: Be lenses at three positions (229, 857 and 962 m downstream of the undulator exit) resulting in spot sizes of ~200 µm, ~20 µm, and 1 – 3 µm FWHM for 5 – 25 keV [2, 3, 4].
- Split & Delay Line (BMBF project, U Münster): Delays: +/-1 ps (24 keV) to +/-23 ps (5 keV) [7].
- Monochromators: 4-bounce $Si_{111}$ (5 – 25 keV, ~$10^{-4}$ ΔE/E) [1], high-resolution monochromator (~$10^{-6}$ ΔE/E) [4].

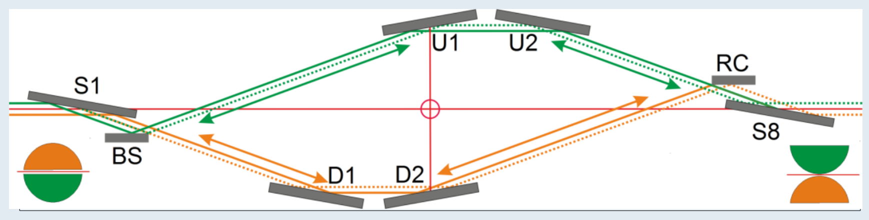
**Mirrors, coating $B_4C$**



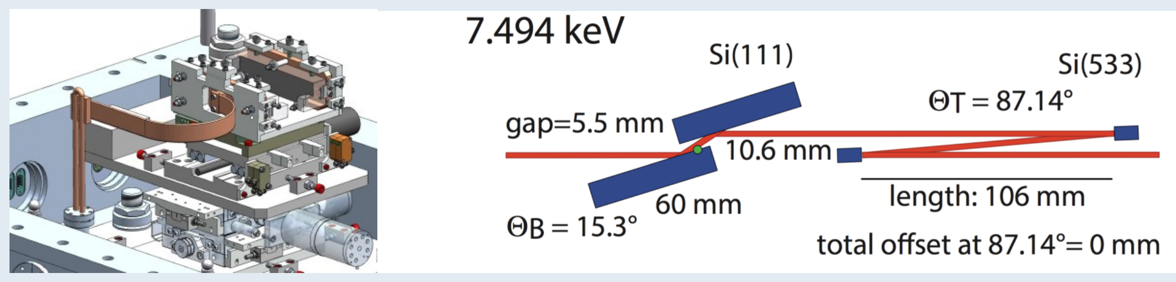

**Focusing concept with CRLs**



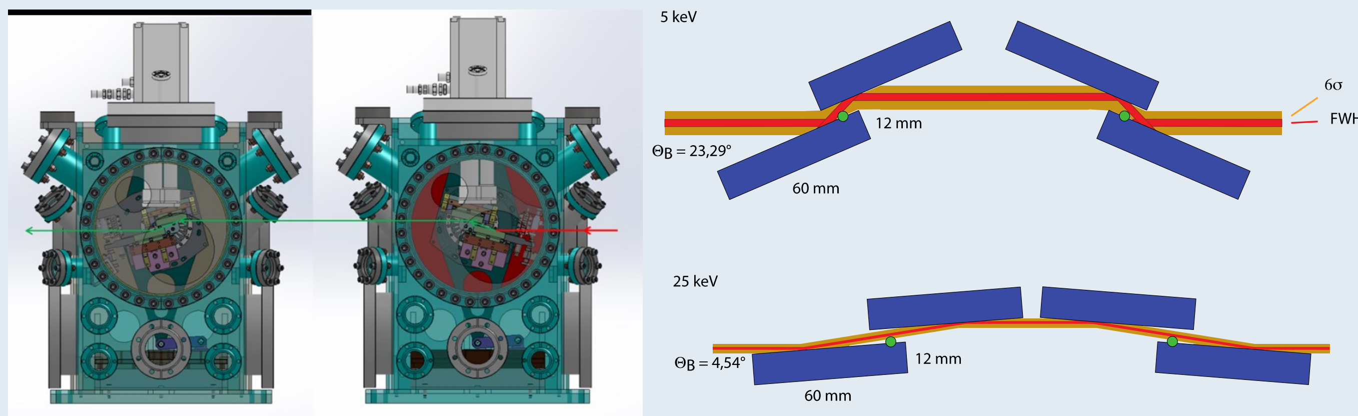
**Split-and-delay unit**



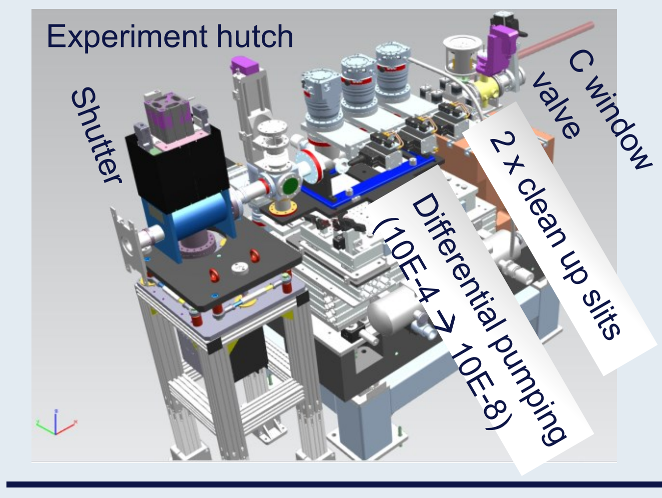

**High-resolution Monochromator**

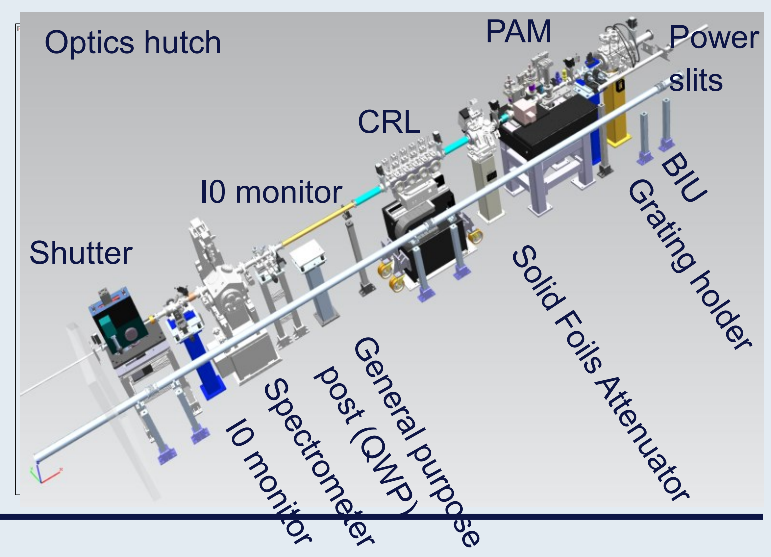



**Four-bounce Monochromator**




## X-ray beam transport





## References

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[2] M. Nakatsutsumi et al., Technical design report: Scientific instrument High Energy Density Physics (HED), XFEL:EU TR-2014-001, Germany, 196 p (2014). doi:10.3204/XFEL.EU/TR-2014-001.
[3] K. Appel et al., Plasma Phys. Control. Fusion 57, 014003 (2015).
[4] M. McMahon and U. Zastrau (eds.), Conceptual design report: Dynamic Laser Compression Experiments at the HED Instrument of European XFEL, XFEL.EU Tr-2017-001 (2017).
[5] M. Nakatsutsumi et al., Plasma Phys. Control. Fusion 59, 014028 (2017).
[6] M. Makita et al., Optica 2(10):912 (2015).
[7] S. Roling et al., Proc. of SPIE Vol. 9210 92100B-2 (2014).


European XFEL GmbH, Karen Appel, Holzkoppel 4, 22869 Schenefeld, Germany, Phone +49 40 8998-2930, Fax +49 40 8998-1905, karen.appel@xfel.eu
**www.xfel.eu**



Bundesministerium für Bildung und Forschung
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Westfälische Wilhelms-Universität Münster
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# Standardized sample holder concept and load-lock exchange system

M. Makita[1], K. Appel[1], C. Baehtz[2], B. Chen[3], C. Deiter[1], S. Di Dio Casifo[2], T. Feldmann[1], S. Göde[1], M. Hassan[2], H. Höppner[2], Z. Konopkova[1], E. Martens[1], D. Möller[2], M. Nakatsutsumi[1], A. Pelka[2], T. R. Preston[1], A. Schmidt[1], K. Sukharnikov[1], I. Thorpe[1], M. Toncian[2], T. Toncian[2], and U. Zastrau[1]

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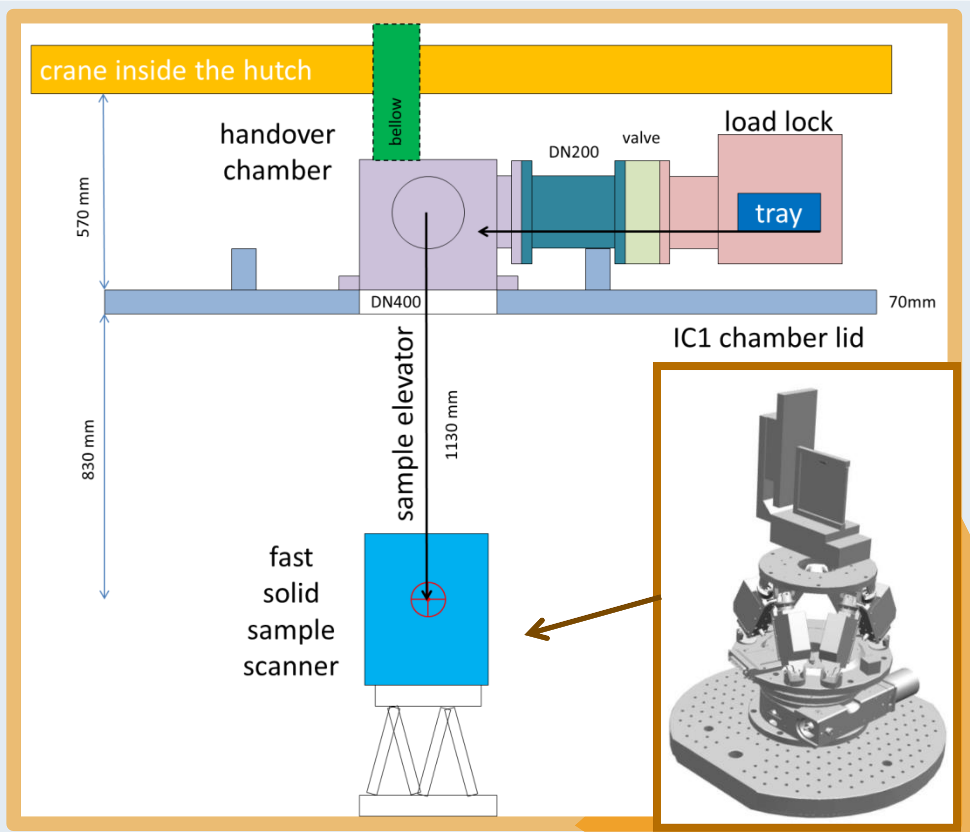
[3] Chinese Academy of Engineering Physics, People's Republic of China

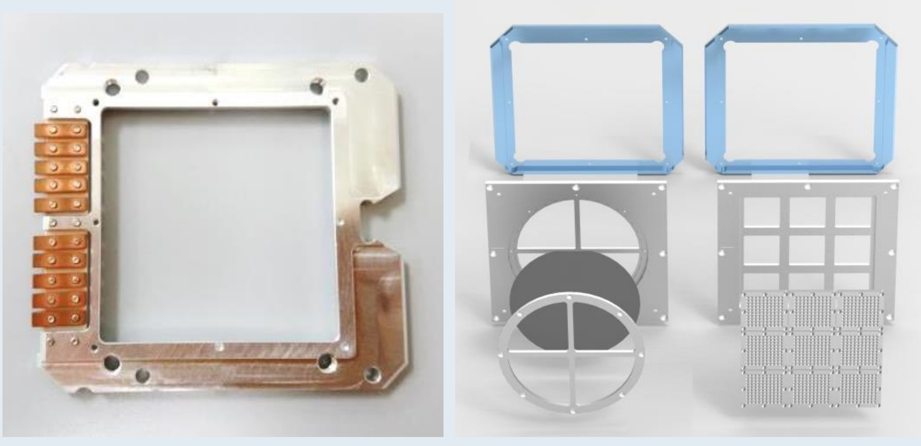



## Solid sample loading

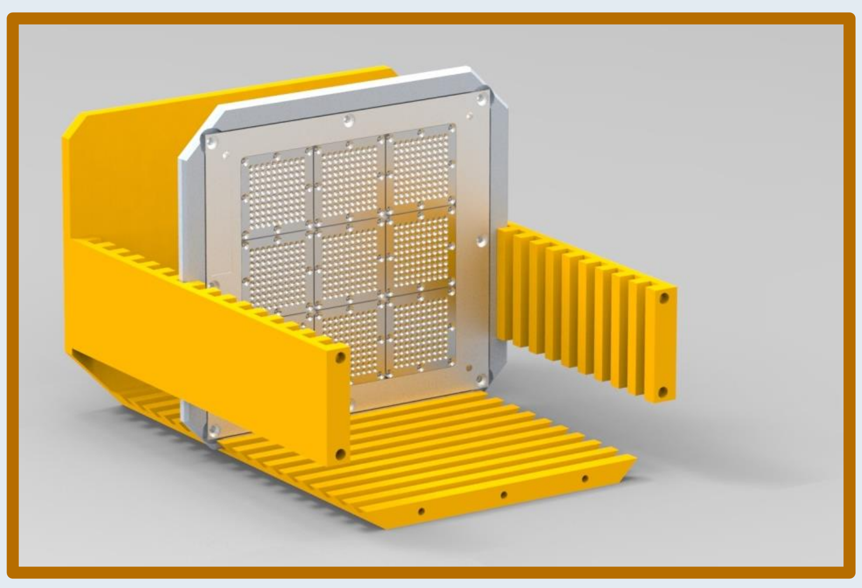
- **[Above]** Load-lock schematic view
  - Gate valve connection to the main interaction chamber (IC)
  - Independent vacuum system to the chamber
  - Positioning of exchanged sample is done with clamps, identification pins & fiducial markers
  - Fast sample scanning x-y motors will be positioned on top of the Hexapod

## Sample holder

- **Standardized** Sample frame & holders
  - (left) Example of the Outer frame.
  - (right) Inner frame, to fit the outer frame. 10cm x 10cm area. Within this dimension, the frame design, geometry and materials can be modified. The sample frame is compatible to those of the ELIMAIA beamline.



- **[Below]** Sample frame holder cassette
  - Holds up to ~8 samples at a time
  - Sample exchange and refilling without breaking the vacuum nor affecting the setup



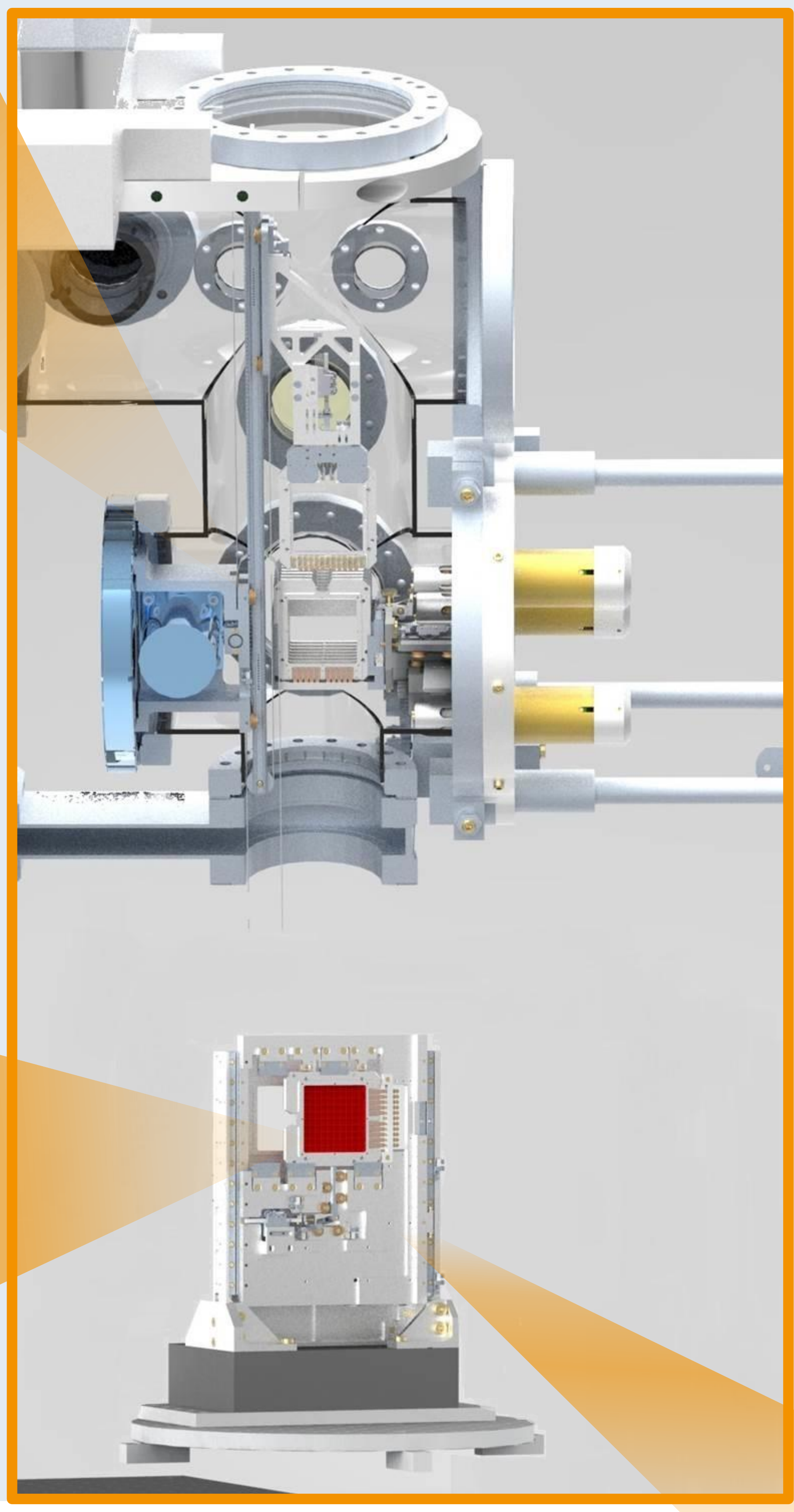
## Introduction

The HED instrument focuses on matter at extreme conditions of temperature, pressure, electric and / or magnetic field. The solid sample holder system employs the standardized design concept from the **EUCALL project (proposal #654220)** which consists of a **two-part** system :

(1) **inner sample frame** standardized outer dimension, and can be modified for specific sample geometry, and

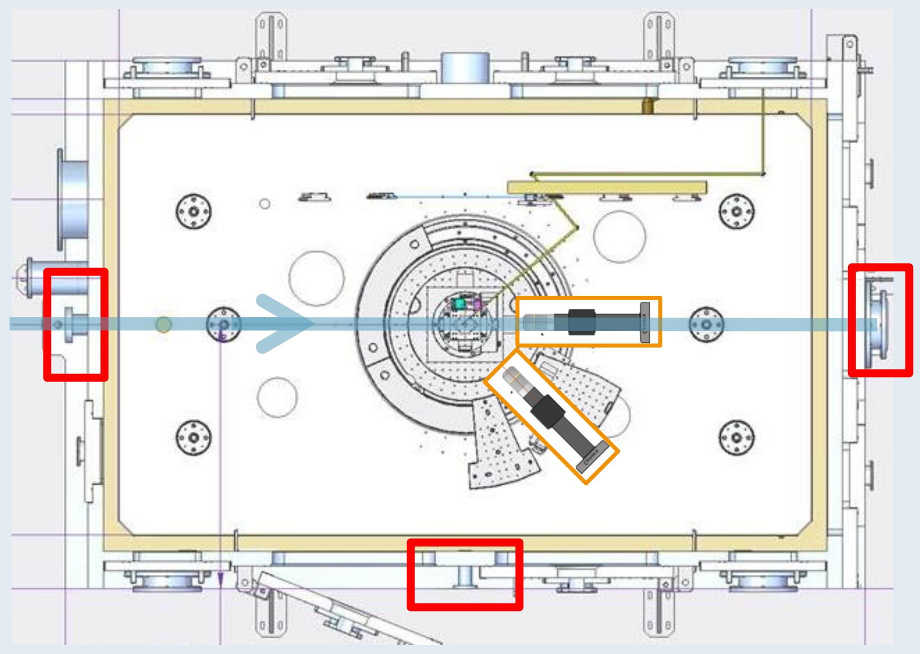
(2) **outer carrier frame** standardized inner dimension, with unique frame design permanently installed for each facility.

The design serves different subsets of user communities to be able to prepare and fabricate samples that are physically compatible at every participating facilities.



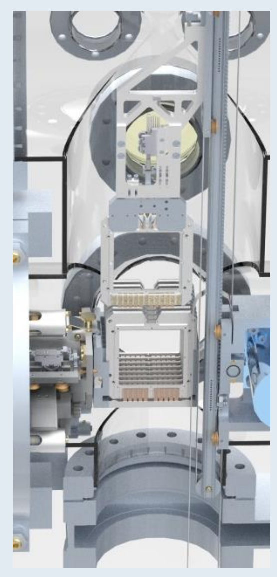
## Sample monitoring

- Long & short distance cameras to monitor the positioning of the sample
  - ~ 3 out-vacuum cameras (red sqrs position) for long-range view
  - 2-3 in-vacuum cameras (orange sqrs) for high resolution adjustment



## Future developments

- Motor for high rep-rate (10Hz) experiments
  - Scan speed, step-size requirements and limits
    – sample dimension (10 x 10 cm^2) limits step-sizes for 10 Hz scanning
  - Protection from energetic electrons generated from the intense pump dynamics
  - Tolerance to EMP from the irradiated targets
  - Installation of motor stage cooling system
- EMP tolerance test
  - Planned experiment in Summer 2018 at HiBEF (Institute of Radiaion Physics, Helmholtz-Zentrum Dresden-Rossendorf)
- Sample exchange arm design
  - ~ 1 m long foldable mechanism
  - Weight tolerance ~ kg.

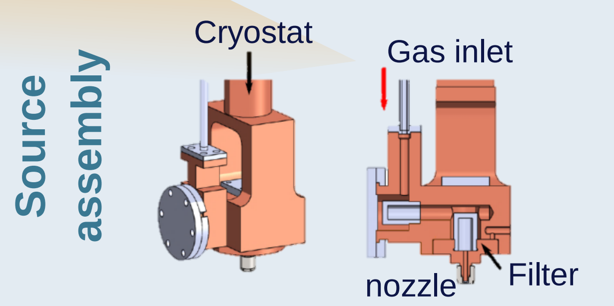


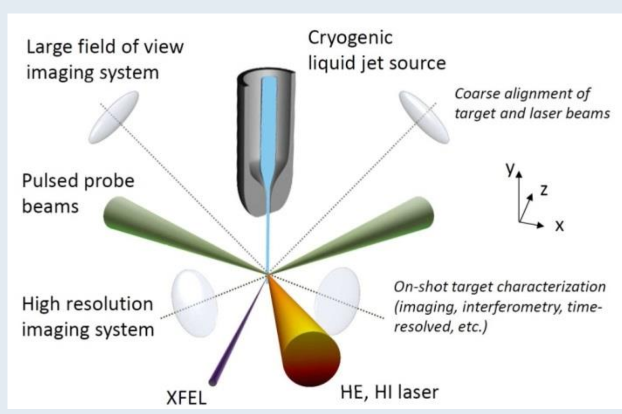
1. C. Deiter et al, EUCALL Grant agreement number: 654220
2. I. Prencipe et al., H.P.L.Sci. and Eng. (submitted)

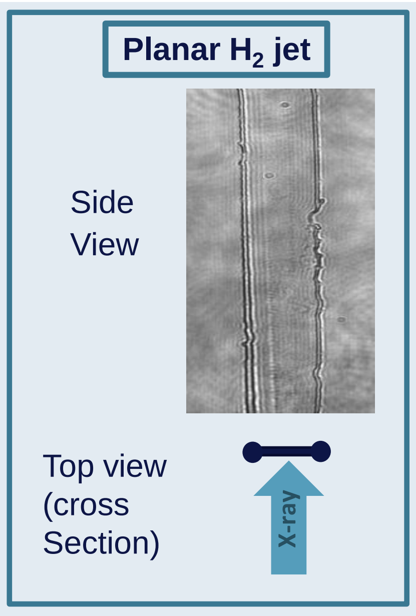
## Liquid Jet samples

- Liquid jets deliver debris-free samples at repetition rate of 10 Hz [3]
- Using cryogenic liquids provide new materials at solid density such as $H_2$, He, $CH_4$, $CO_2$, ...
- Jets with planar/flat geometries with variable thickness enable controlled dynamic shock compression studies
- Laser driven protons from liquid $H_2$ jets may be applied for isochoric heating studies
- Development of a platform for routine application of liquid jet techniques at HED under investigation

Source assembly




3. J. Kim, S. Göde et al, RSI 87, 11E328 (2016)

European XFEL GmbH, Mikako Makita, Holzkoppel 4, 22869 Schenefeld, Germany, Phone +49 40 8998-6785, Fax +49 40 8998-1905, mikako.makita@xfel.eu
www.xfel.eu

ENLIGHTENING SCIENCE

# Status of the Diamond Anvil Setup for the HED instrument of the European XFEL.

H.-P. Liermann[1], Z. Konôpková[2], A. Schropp[1], C. Strohm[1], K. Appel[2],U. Zastrau[2], H. Damker[1], M. Foese[1], C. Baehtz[3]

[1]Photon Sciences, Deutsches Elektronen Synchrotron, DESY, Hamburg, Germany
[2]European XFEL, Hamburg, Germany
[3]Helmholtz-Zentrum Dresden Rossendorf, Dresden, German

## Abstract:

**The HED instrument at the European XFEL offers the unique opportunity to develop new experimental capabilities to explore planetary physic of solar and extra solar planets using new static and dynamic DAC x-ray diffraction techniques. Within this poster we describe some of the current ideas to make optimal use of these DACs at the European XFEL and present the current status of the design for a DAC setup for the HED instrument funded within the HIBEF consortium.**

### Introduction:

Time resolved diffraction at simultaneous high-pressure and -temperatures as well as fast compression/heating is an emerging field in static/dynamic high-pressure physics. This technique may be used to determine Equation of State (EOS) and phase stability at very high pressures and temperatures using the double stage Diamond Anvil Cell (dsDAC, Dubrovinsky et al. 2012) and the dynamic Diamond Anvil Cell (dDAC, Evans et al. 2007), which is not achievable with conventional static high-pressure techniques. In addition one may explore the effects of changing compression rates on the location and kinetics of solid-solid as well as solid-liquid phase transitions using the dynamic Diamond Anvil Cell (dDAC). While dynamic compression diffraction experiments are possible at 3rd generation sources in the kHz (µs) regime , it will require new 4th generation sources, such as the European XFEL, to be able to conduct time resolved experiments in the MHz (ns) regime.

Since July of 2015 we have been developing a DAC setup for the “Helmholtz International Beamline for Extreme Fields” (HIBEF) user consortium lead by HZDR and DESY. Below we describe the current status of the design for of the DAC setup to conduct time resolved dynamic compression experiments in the dsDAC and dDAC.

**Idea:** Perform burst of single shot x-ray diffraction measurements at 4.5 MHz to get EOS of a material in 5 µs (25 bunches) before dsDAC fails.

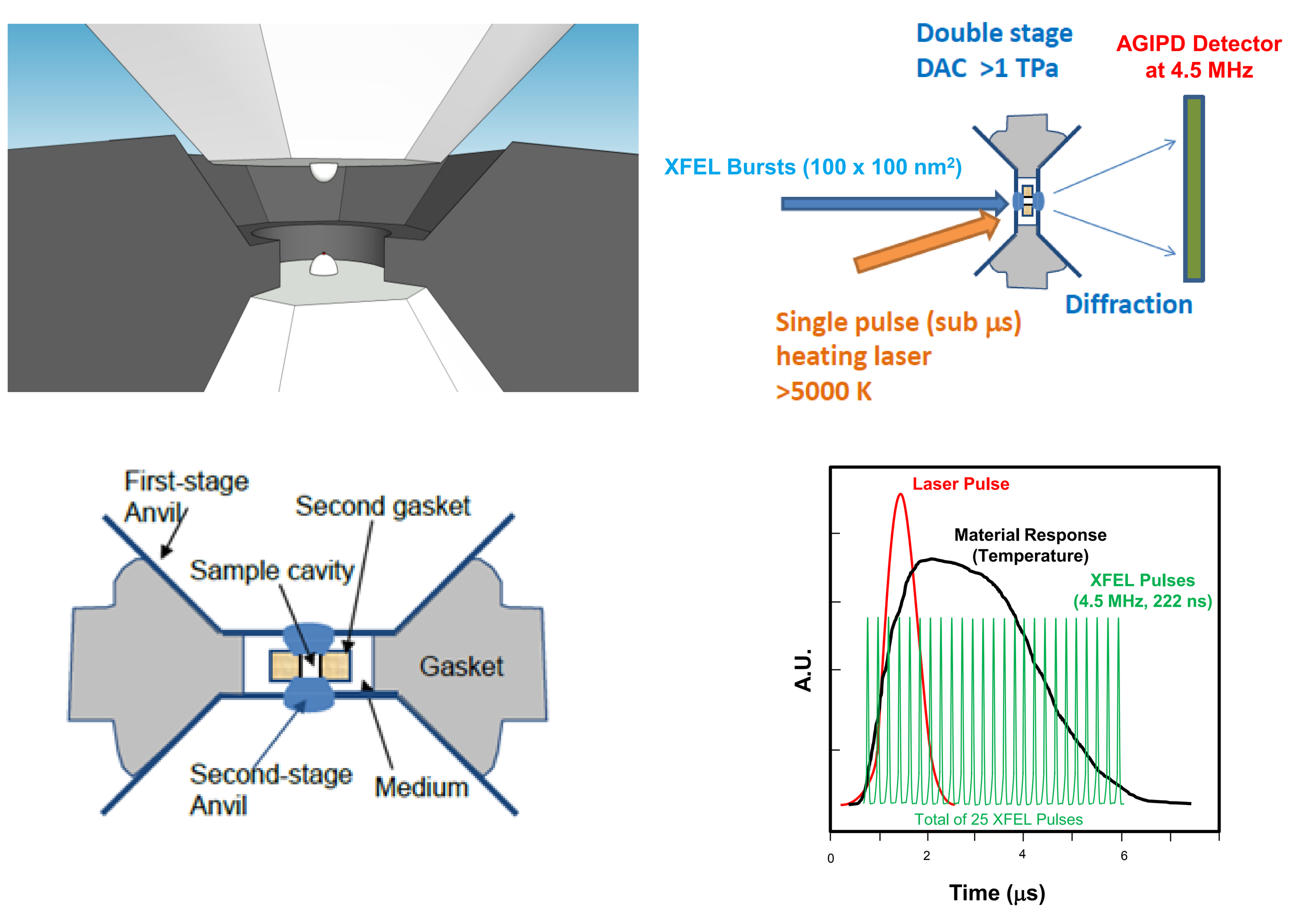



**Fig. 1 Left:** Schematic description of the double stage setup used by Dubrovinsky et al. (2012). **Right:** Conceptual experimental setup for conducting dsDAC experiments and laser heating using a 1 us laser heating pulse and the 4.5 MHz repetition mode of the XFEL for collecting diffraction images. One may collect 25 diffraction images over approximately 6 us of material response. The material response does not take into account the effect of isochoric heating when using a very small x-ray beam (see Fig. 3).

**Idea:** Perform single shot x-ray diffraction measurements at 0.5 MHz to determine EOS of a compound in one pulse train (600 µs) before diamonds are destroyed by reactive compounds ($H_2$, $H_2O$ ,….).

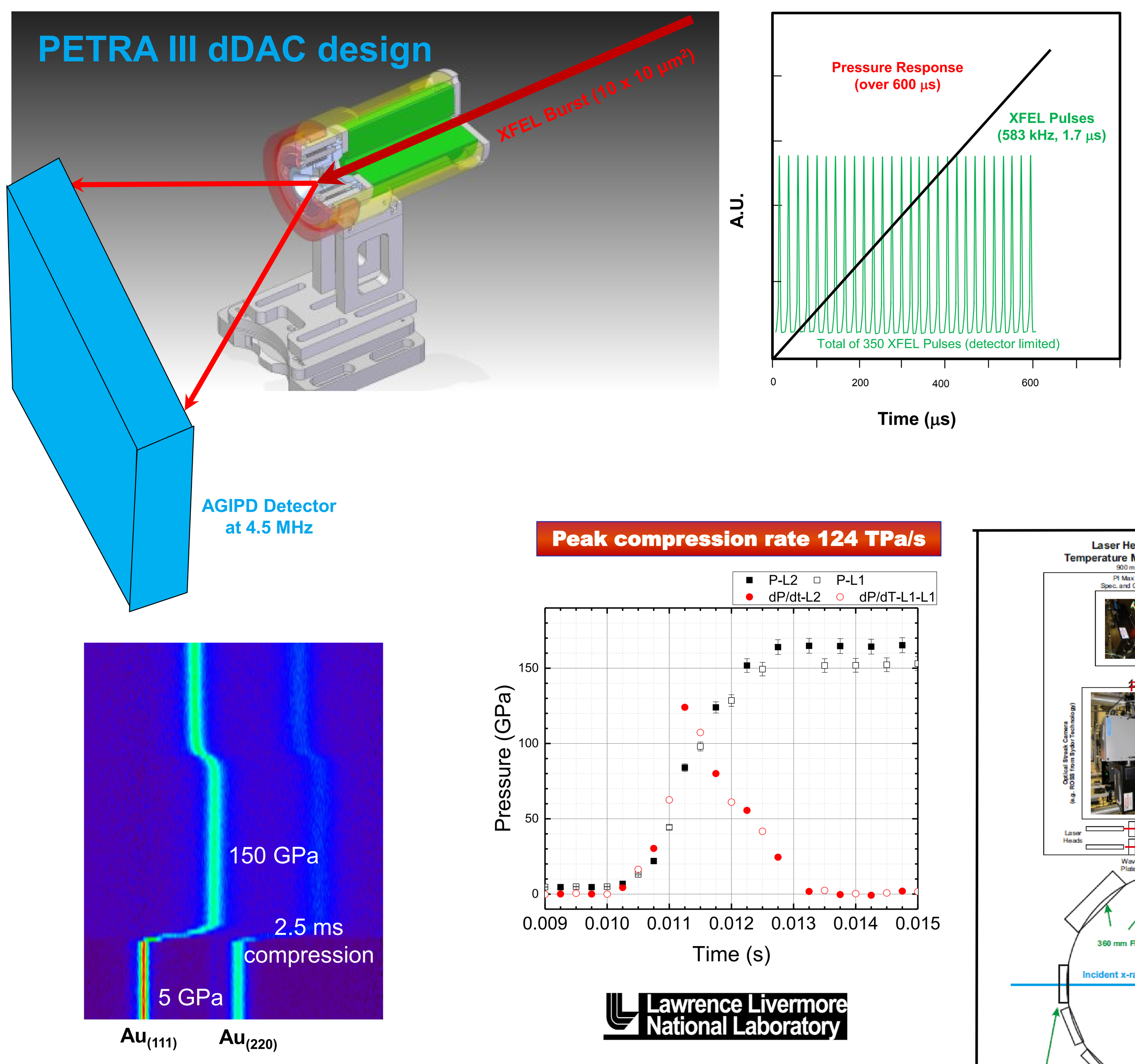



**Fig. 2 Top:** New dDAC design from DESY. **Bottom:** Fast compression of Au in the dDAC at the bemline p02.2 (ECB, PETRA III). Collaboration with LLNL high pressure group (PI W. Evans, courtesy of Z. Jenei)

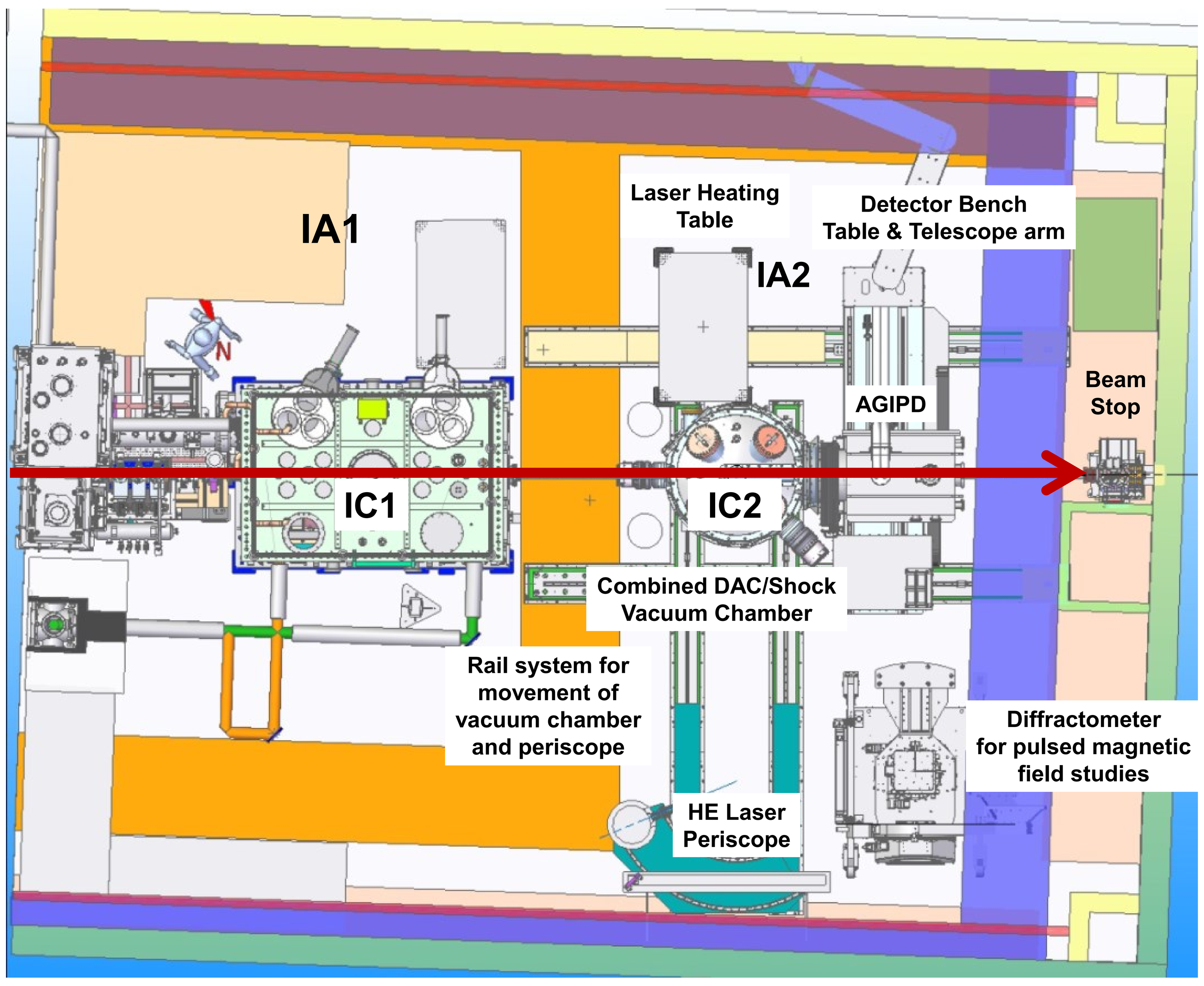



**Fig. 3:** Top view of the experimental hutch of the HED instrument with two interaction areas (IA1 and IA2). Located in IA2 is the 2nd interaction chamber (IC2) for either DAC work or standardized shock compression work with the High-Energy Dipole laser. The IC2 sits on a rail system and can be placed at the side of the HED hutch The IA2 may also be used for pulse magnetic field studies or other sample environments.

### Design of the Interaction Chamber 2 (IC2) housing the DAC setup at the HED instrument

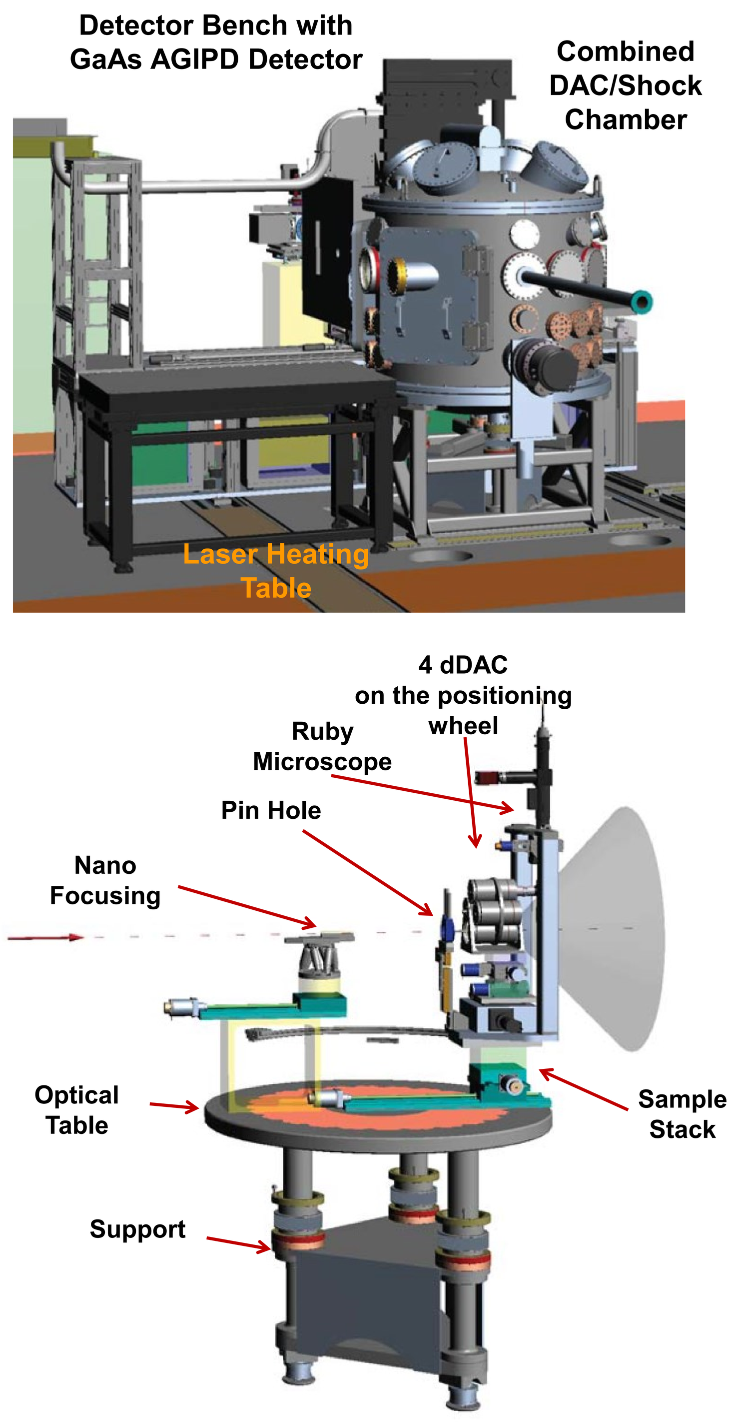
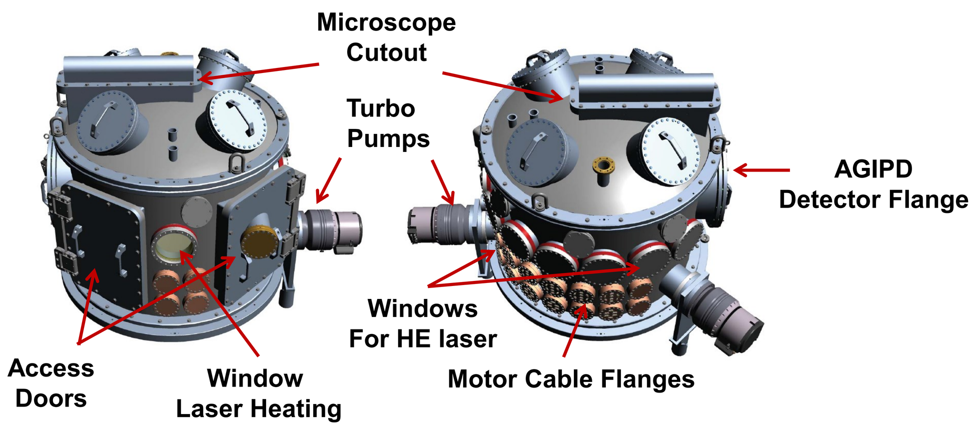



**Fig. 4 Top:** Current design of the IC2 vacuum vessel to be placed at the IA2 for combined DAC/Shock experiments. **Bottom:** Inside of the IC2 indicating the dDAC setup.




### Access to Reciprocal Space in the DAC Vacuum Chamber

**Requirements**

- 2θ angle limited by DAC opening (45°)
- 2 =+/−45° covers d = 0.648 Å or Q = 9.7 Å$^{-1}$ @25 keV
- To cover +/-45° opening with a PE or AGIPD SDD = 200mm
- Difficult when DAC in the center => move DAC 300 mm from the center

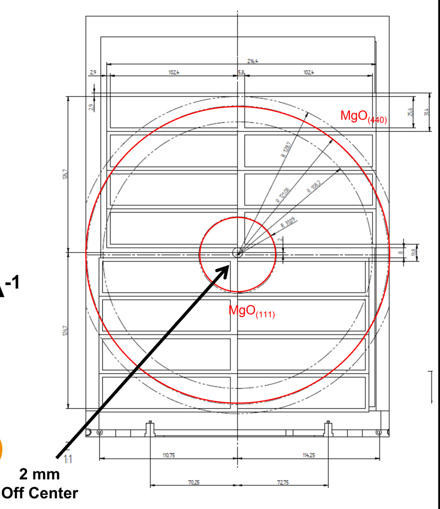
**Design Established**

**At 200 mm SSD:**

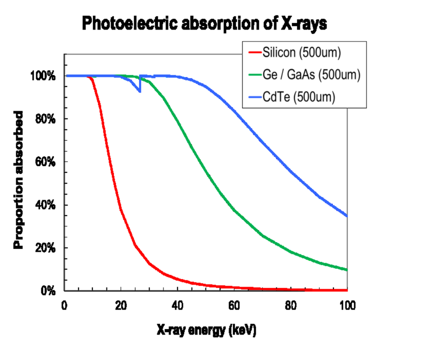
- Horizontal 2θ = 28.5°,d = 1.008Å, q = 6.23Å$^{-1}$
- Vertical 2θ = 32.8°, d = 0.878Å, q = 7.153Å$^{-1}$

**At 150 mm SSD:**

- Horizontal 2θ = 35.8°, d = 0.807Å, q = 7.787Å$^{-1}$
- Vertical 2θ = 40.8°, d = 0.711Å, q = 8.831Å$^{-1}$

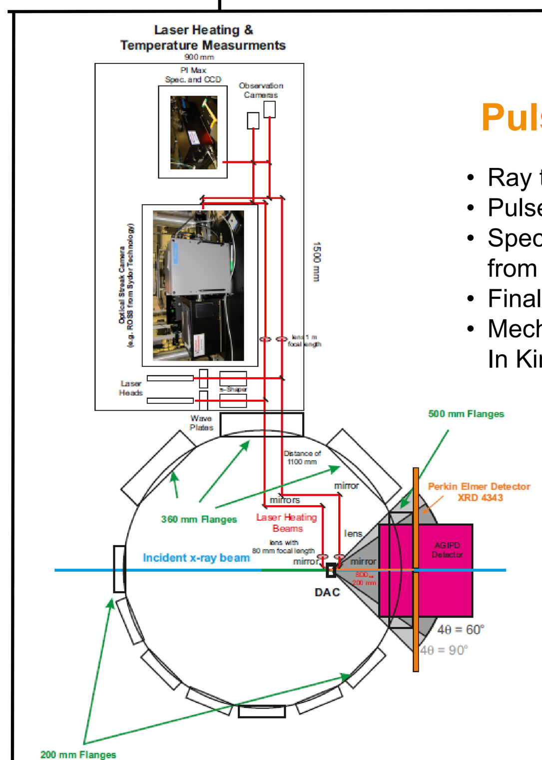



### GaAs AGIPD
### (Adaptive Gain Integrating Pixel Detector)




cification:
aAs sensor (100 % QE @ 25 keV)
ingle photon counting up to ~10$^4$
ı/pixel/frame
ixel 0. 2 x 0.2 mm² pixel size
ize: 1024 × 1024 (200 x 200 mm active area)
lax frame rate: 4.5 MHz (burst mode)
acuum compatible

### Double Sided Pulse Laser Heating System




- Ray tracing => ongoing (Z. Konopkova, HED)
- Pulsed Lasers => ordered from DFG funding
- Spectrometer + Streak Camera => Ordered from HED funding
- Final Design => middle of the year
- Mechano Optics => funding thorough DESY In Kind contribution to HIBEF project

**Fig. 5:** Conceptual design of the double sided pulse laser heating experiment for the DAC setup for the HED instrument.

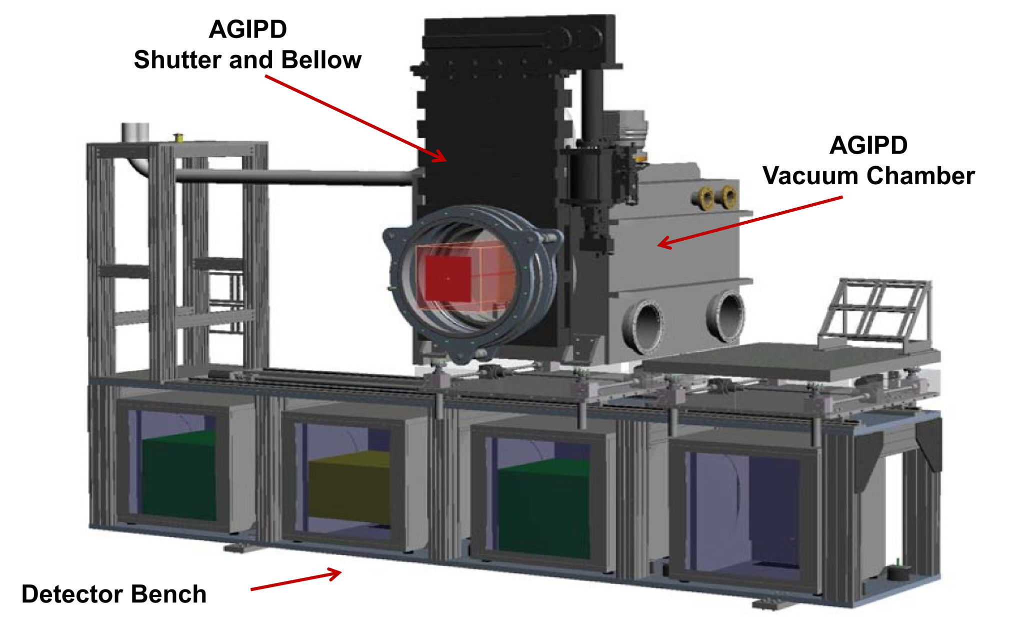



**Fig. 6:** Current design of the detector bench that will carry the AGIPD detector as well as other relevant detectors for the experiments at IA1 & IA2.

**References:**

- Dubrovinsky et al. (2012) Nature Commun. 3, 1163.
- Evans et al. (2007) Rev. Sci. Instrum., 78, 073904.

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